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Preliminary Data on the Field Performance of Storage-Type Residential Water Heaters

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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*

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by

Richard A. Grot and Lawrence S. Galowin

ABSTRACT

The early results of a field experiment for determining the performance of gas and electric residential storage water heaters are presented. Energy requirements for hot water supply and hot water consumption and usage pattern data are presented and analyzed using statistical techniques in order to display average load curves and the variation about the average. It is shown that the daily energy usage of these water heaters is approximately a linear function of the energy content of the drawn daily water consumption. This fact allows a simple procedure to be used for evaluating the effects of retrofit actions on the performance of the water heater.

Keywords: Energy usage; load profiles; water heaters.

UNITS OF MEASURE AND S.I. CONVERSION FACTORS

In NBS Document LC 1056, revised August 1975, guidelines were established to reaffirm and strengthen the commitment of NBS to the greatest practicable use of the International System of Units (S.I.) in all of its publications and also in all of its dealings with the science and engineering communities and with the public. In this report the measurements are those of the U.S. customary units as they appear in the referenced standards, in order that the readers may give full attention to the organization and compilation of the criteria.

The following conversion factors are appropriate for the units of measure that appear in this report:

Energy

1 British thermal unit (Btu) = 1055.056 joule (J)
1 kilowatt-hour (kWh) = 3600000.0 joule (J)

Temperature

1 degree Fahrenheit (°F) = $(1.8)^{-1}$ kelvin (K) or (°K)
Temperature Fahrenheit (°F) = (459.67 + temp. °F)/1.8 (°K)

Time

1 hour (h) = 60 minutes (min) = 3600 seconds (s)

Volume

1 U.S. liquid gallon (gal) = 0.003785412 meter^3 (m^3)
= 3.785412 liters (L)

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FIGURES

Table 2. WATER HEATER CHARACTERISTICS

Electric Water Heaters

Unit No.	Manufacturer	Model	Capacity gal	Input watts
1	Westinghouse	TB802LKKX0	82	4500/4500/4500
2	Westinghouse	TB802LKKX0	82	4500/4500/4500
5	Westinghouse	TB802LKKX0	82	4500/4500/4500
6	Westinghouse	TB802LKKX0	82	4500/4500/4500
9	Westinghouse	TB802LKKX1	82	4500/4500/4500
10	Westinghouse	TB802LKKX1	82	4500/4500/4500

Gas Water Heaters

	Manufacturer	Model	Capacity gal	Input Btu/h
3	Bradford	40DBF5N-1	40	45000
4	Bradford	40DBF5N-1	40	45000
7	Bradford	40T5	40	48000
8	Bradford	40T5	40	48000
11	Bradford	40T5	40	48000
12	Bradford	40T5	40	48000

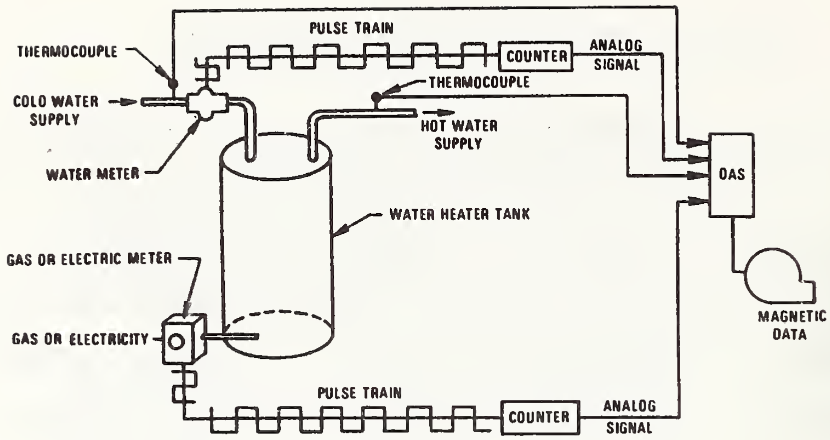

Figure 1. Water Heater Data Acquisition Schematic

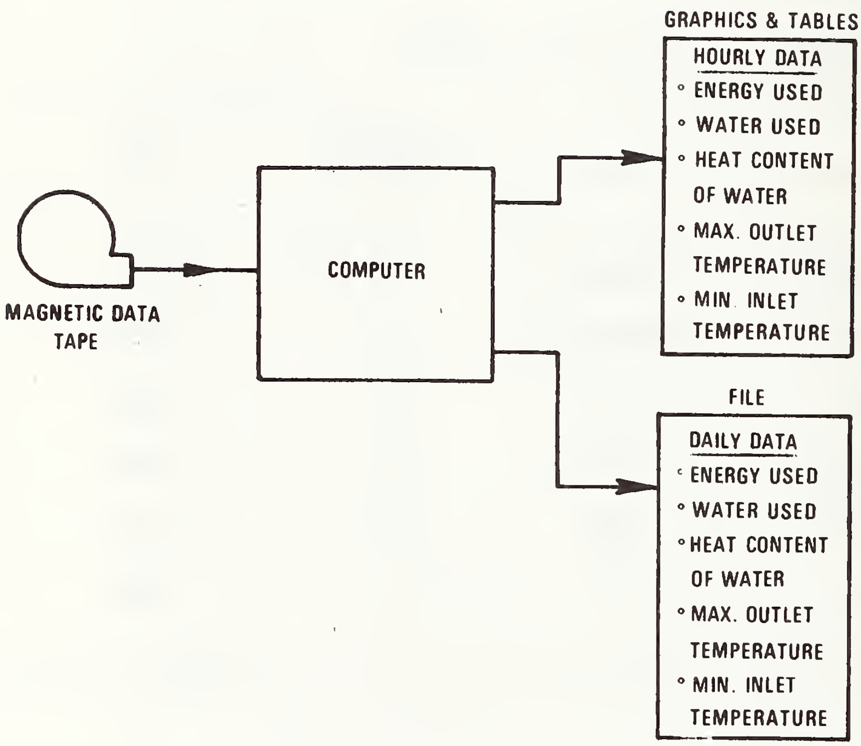

Figure 2. Simplified Data Processing - Output Schematic

PRELIMINARY DATA ON THE FIELD PERFORMANCE OF STORAGE TYPE RESIDENTIAL WATER HEATERS

1. Introduction

The early results of a field experiment for determining the performance of gas and electric residential storage water heaters are presented. Energy requirements for hot water supply and hot water consumption and usage pattern data are presented and analyzed using statistical techniques in order to display average load curves and the variation about the average. It is shown that the daily energy usage of these water heaters is approximately a linear function of the energy content of the drawn daily water consumption. This fact allows a simple procedure to be used for evaluating the effects of retrofit actions on the performance of the water heater.

2. Test Program

The data discussed in this article were collected as part of an effort to evaluate the performance of eight major household appliances under the Energy Appliance Labeling Program. The test measurements were made in single-family townhouse residences in Twin Rivers, N.J., near Princeton University. The choice of this site was motivated by prior studies under a program for Energy Husbandry in Housing; extensive knowledge about the homes and occupants was available from instrumentation located in several of the dwellings. Table 1 identifies the household composition of each townhouse of this study: the number of adults, the number of children, the ages of the children and the size of the townhouse. Each townhouse was equipped with a dishwasher, clothes washer and 1 1/2 baths, the full bath containing a shower-tub combination. Table 2 presents the water heater information of primary interest here.

3. Measurement Method

The data discussed in this article were collected by means of instrumentation and automatic data recording systems; the data tapes were processed by computer programs developed especially for this data reduction. The instrumentation scheme for the water heater is depicted in Figure 1. Ordinary gas, electric and water meters were modified to produce a pulse rate proportional to the rate of usage of the quantity monitored. The pulse train from the meter was fed into a specially designed counter which produced an analogue signal proportional to the number of pulses received in an interval of time. These analogue signals were recorded by a data acquisition system along with the outputs of thermocouples attached to the inlet and outlet water lines. The thermocouples were wrapped with insulation in such a way that any transfer from the ambient air was negligible. The data acquisition system scanned the data at least once every five minutes; thus, in principle, 5-minute energy, water and temperature data were available.

Table 1. OCCUPANT AND TOWNHOUSE CHARACTERISTICS

Unit No.	No. of Adults	No. of Children	Children's Ages	Bedrooms
1	2	2	6,8	3
2	2	1	6	3
3	2	1	3	2
4	2	3	6,7,9	3
5	2	2	10,13	3
6	2	2	10,13	4
7	2	2	2,4	3
8	2	2	1,3	3
9	3	1	15	3
10	2	2	2,6	2 converted to 3
11	2	2	11,13	3
12	2	2	5,11,4	3

To the present, however, the data analysis has been confined to time intervals consisting of either one hour or one day. The hourly and daily data were printed in summary form (see Table 3 or graphs, Figures 3 - 8) and also outputed to mass storage files for later data analysis (see Figure 2). In Table 3 representative data for a limited number of days are illustrated for Townhouse 10.

4. Discussion of Results

The homes comprised several with gas-fired appliances and others with electric, as indicated in Table 2. The data discussed in this report are for the electric installations and treat only the water heater. Representative data are presented which illustrate the usage patterns, water consumption, energy content and energy required for heating the water. The electric water heaters have an 82-gallon capacity and are rated at 4500/4500/4500 watts with manufacturers' data sheets providing other specifications.

Townhouse number 10 represents a household of two adults and two children, ages 2 and 6. Figures 3, 4, 5 represent the hourly distribution of water and energy used during a four-day period in the Christmas holiday of 1976. In Figure 3 the hot water usage is shown to be less than 25 gallons in any hour. The energy content of the water used and the energy required for heating are presented in Figures 4 and 5. The periods of time from zero to ten hours of days 360 and 361 are of special interest in that very little water consumption occurs so that heating of the incoming cold water supply is at a minimum. The energy required for heating to make up for stand-by losses can be observed by noting the isolated usage of 0.8 kWh about every 5 or 6 hours in the night. At other times it is necessary to establish the heat balance equation to compare the heat addition required to make up for the heat removed by the usage due to the replenished supply of incoming cold water and then to raise the temperature of the mass of the water stored in the tank.

The range of temperatures measured on the hot water supply line (see Figure 1) are shown in Figure 6. The thermocouple mounted on the pipe does not provide the stored water temperature. When there is no hot water flow the reading represents only the pipe wall temperature due to heat conduction from the tank; during periods of flow the wall temperature measurement is very close to the water within the pipe. The differential of the control sensor element within the hot water heater appears to be approximately 5°F for delivery of hot water except during periods of heavy demand. The temperature of the incoming supply of water (measured as for hot water) is indicated in Figure 7. The temperature is close to 55°F. In Figure 7 the minimum value during each hour interval is shown in order to obtain the representative situation when cold water is flowing (rather than the idle pipe wall temperature or some intermediate value).

Table 3. WATER HEATER CONSUMPTION--TOWNHOUSE 10

Day	Energy (kWh)	Water (gal)	Heat Content of Drawn Water (kWh)
283	13.97	37.50	8.77
284	17.09	50.40	11.97
285	22.27	68.90	16.31
290	15.62	46.20	10.44
291	12.16	28.20	6.64
292	32.70	108.20	25.53
293	18.60	57.20	13.77
294	34.30	114.80	27.34
295	23.19	73.40	17.53
296	26.32	86.10	20.31
297	14.26	38.40	9.07
298	19.45	60.70	14.35
299	16.44	49.10	11.48
300	31.17	99.40	23.49
301	21.91	74.20	17.93
302	14.73	38.70	9.24
303	31.45	104.10	25.09
304	20.57	62.90	15.28
305	16.88	48.70	11.64
306	34.54	119.50	28.25
307	22.07	69.90	16.86
308	40.75	140.20	33.47
309	15.88	40.00	9.55
310	30.80	107.20	24.38
311	15.90	41.00	9.87
314	28.08	91.50	22.26
315	34.89	115.60	28.51
316	19.07	57.20	13.80
317	21.42	61.00	14.95
318	22.31	67.40	16.73
319	12.61	30.00	7.24
320	28.25	88.60	22.03
321	25.33	82.10	19.90
322	41.84	140.20	34.28
323	17.32	47.10	11.59
324	29.85	94.30	23.32

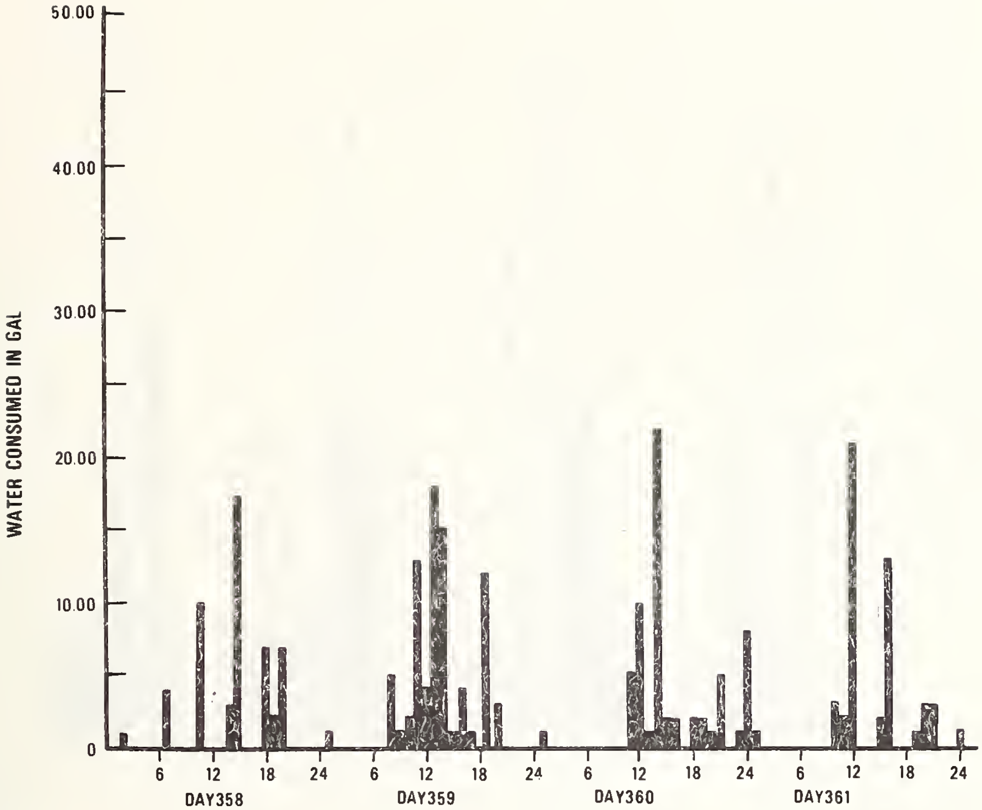

Figure 3. Hourly Hot Water Usage - Townhouse #10

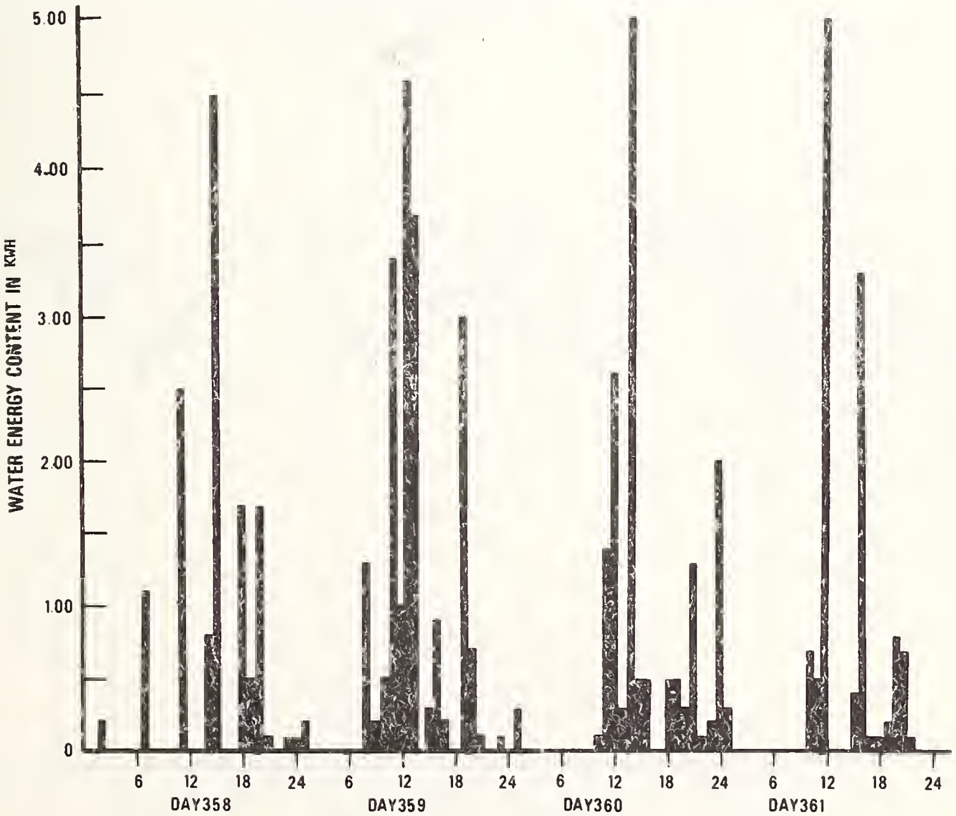

Figure 4. Hourly Energy Content of Drawn Hot Water - Townhouse #10

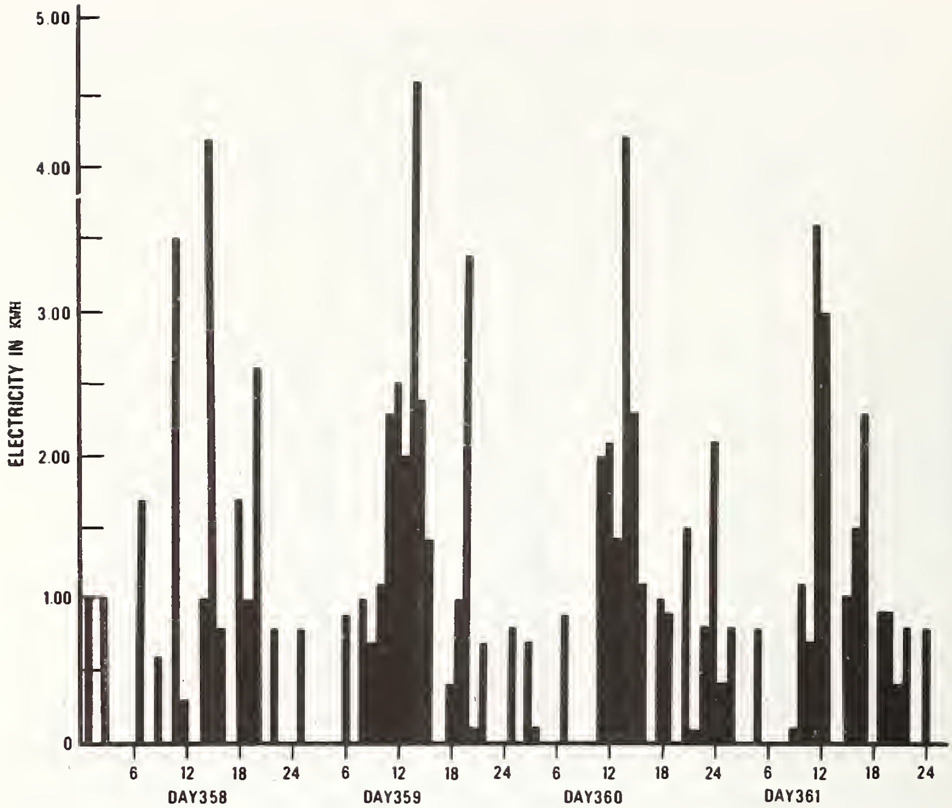

Figure 5. Hourly Energy Usage for Water Heating - Townhouse # 10

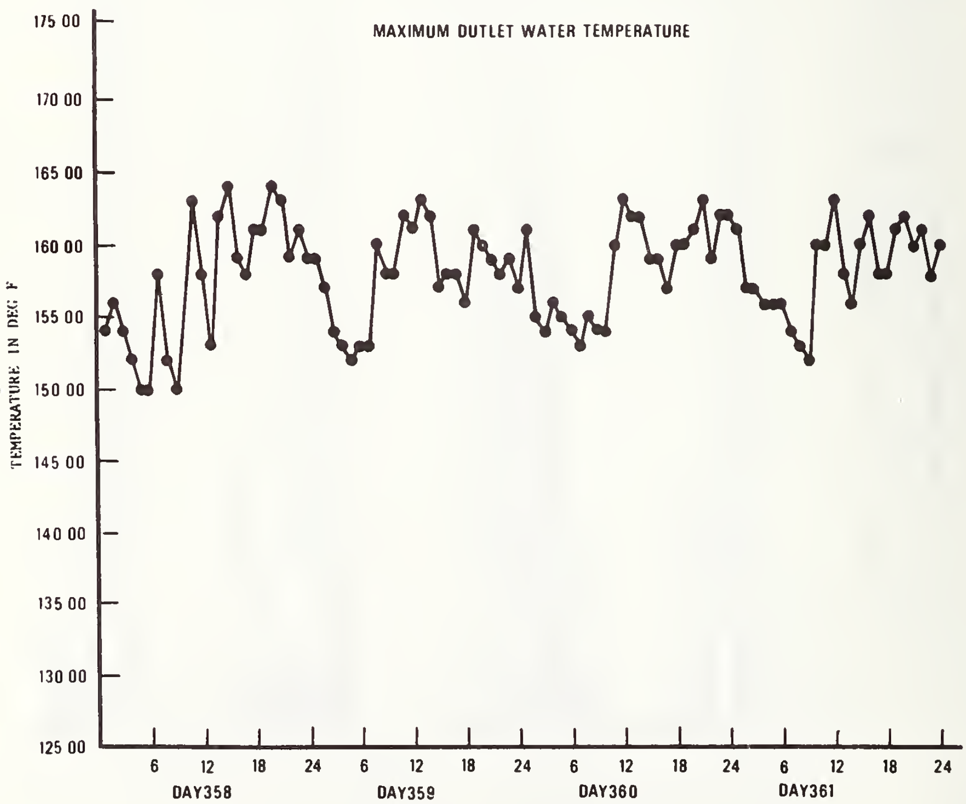

Figure 6. Hourly Maximum Outlet Water Temperature - Townhouse # 10

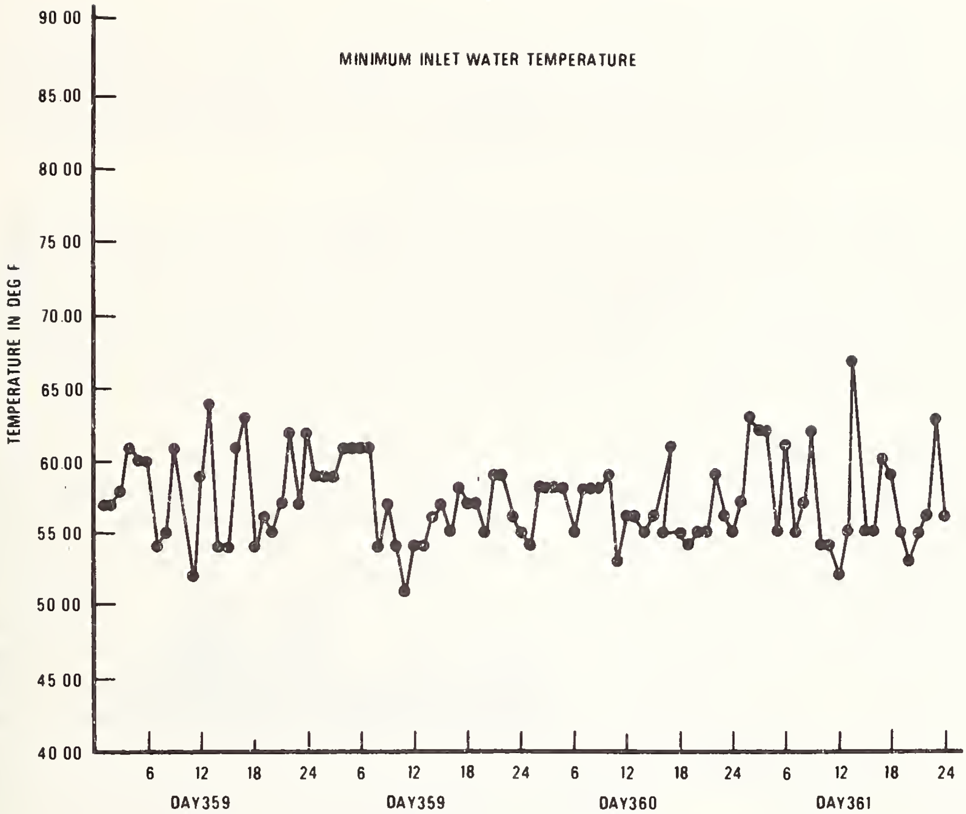

Figure 7. Hourly Minimum Inlet Water Temperature - Townhouse #10

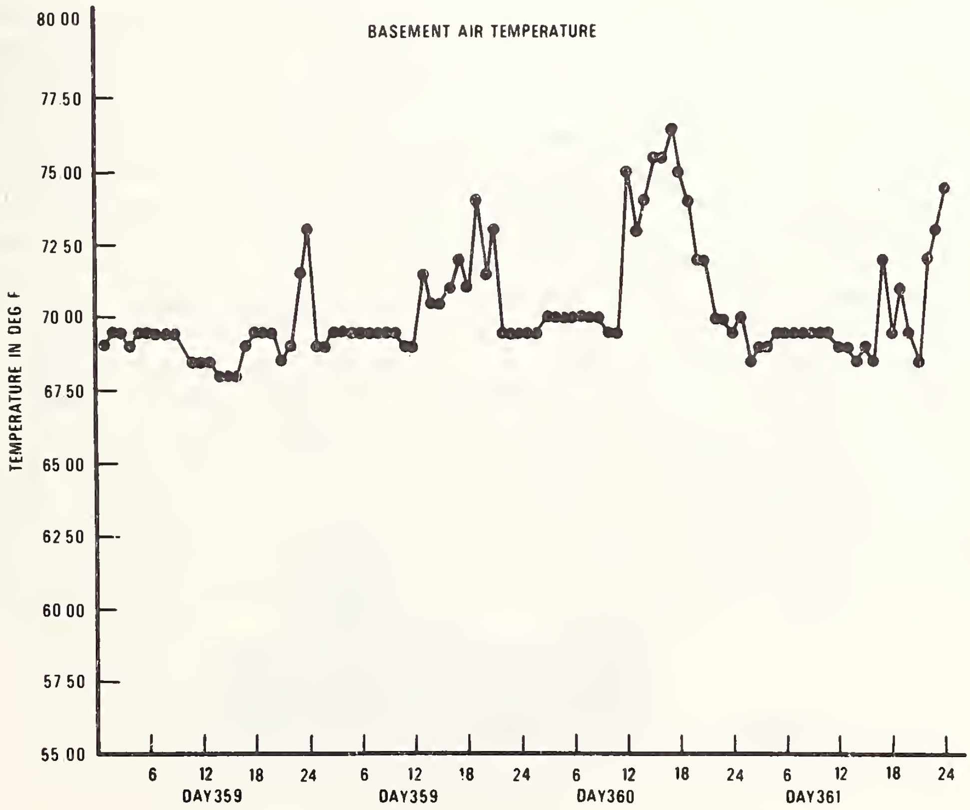

Figure 8. Hourly Basement Air Temperature

Figure 8 shows the temperature in the basement areas where the hot water storage tank is located. In this home the hot air furnace and distribution ducts are in the basement so that for periods during which heating occurs, the basement temperature rises; those events are mostly noted in the late afternoons and evenings.

Further examination of the data from Townhouse 10 is presented in Figures 9-13. The frequency plots are presented of water consumption and energy for water heating for more than 60 days. Table 3 represents a partial history for 36 days of the corresponding daily utilization of energy required for hot water in kWh, hot water consumed in gallons per day and the heat content of the hot water consumed in kWh units.

The frequency graph in Figure 9 shows that the greatest hot water consumption ranges over 60-70 gallons per day and 40-50 gallons per day, each occurring about 16% of the time. The extreme minimum lies between 20-30 gallons with a frequency of about 2% of the time and the maximum 140-150 gallons usage occurs with a probability of 4% of the time. From examination of the data from other homes, it is known that there are significantly ranging diversity factors between occupants demand/usage pattern and consumption. Figure 10 shows a corresponding frequency plot for the daily water heater energy usage. The most frequent range of energy consumption is between 15 and 20 kWh, with an occurrence of 29%. The minimum daily energy usage of between 10 and 15 kWh has an occurrence of 14%; the maximum usage range of 40 to 45 kWh occurred about 4% of the time.

The graphs of Figures 11, 12, and 13 illustrate the essentially linear relationship between the daily energy consumed or daily energy content of the drawn hot water and the water consumed. The data collected seem to indicate that for intervals of a day, storage and transient effects are negligible and the water heater performs in a linear manner. From linear extrapolation of the data in Figures 11 and 12, the standby losses of the hot water storage tank are about 4.5 kWh per day. Since the data demonstrate the linear dependency between the parameters, the standby losses due to conduction, convection, and radiation losses together are nearly a constant increment of energy consumed. In Figure 13 the linear extrapolation through the origin of the data relationship for energy content of the water vs. water consumption provides a level of confidence for the results. Since the operating range of temperatures of the water and the elements of the tank is narrow, non-linear temperature factors affecting the temperature-dependent properties tend to be a constant small part of the losses or are perhaps negligibly small in the loss terms for time intervals of a day or longer. This frequency also indicates that, even at maximum daily usage, the water heater is capable of maintaining the required hot water temperature.

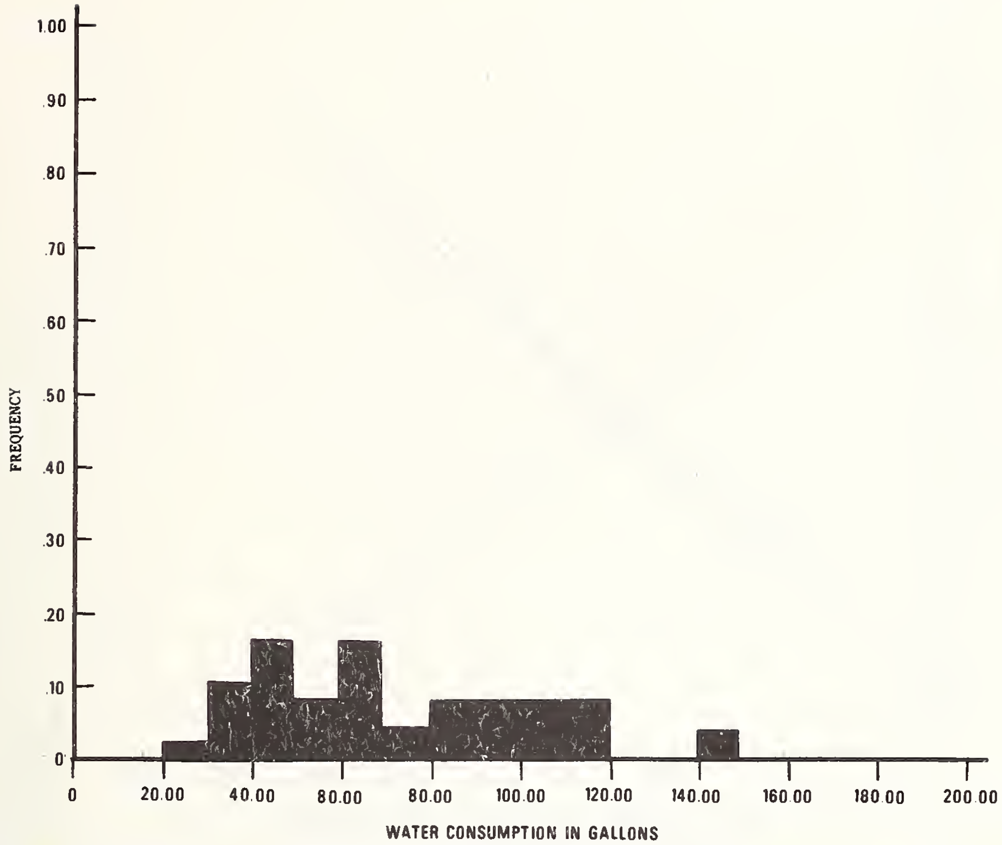

Figure 9. Frequency Plot of Daily Hot Water Consumption - Townhouse #10

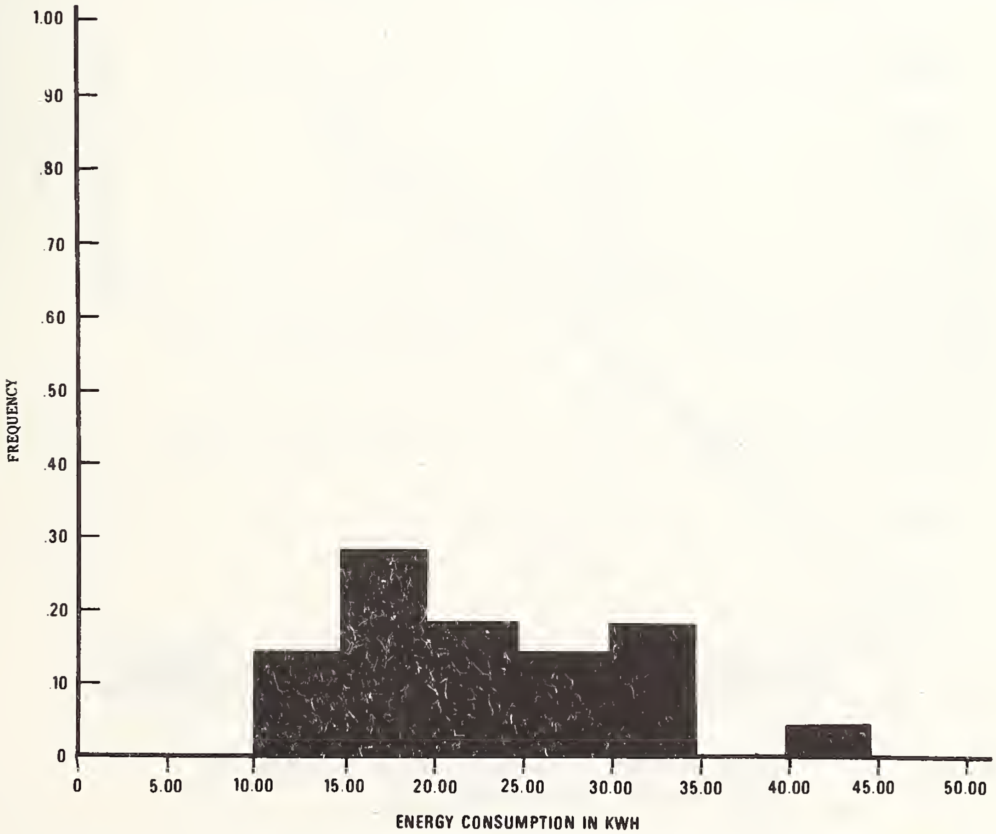

Figure 10. Frequency Plot of Daily Energy for Water Heating

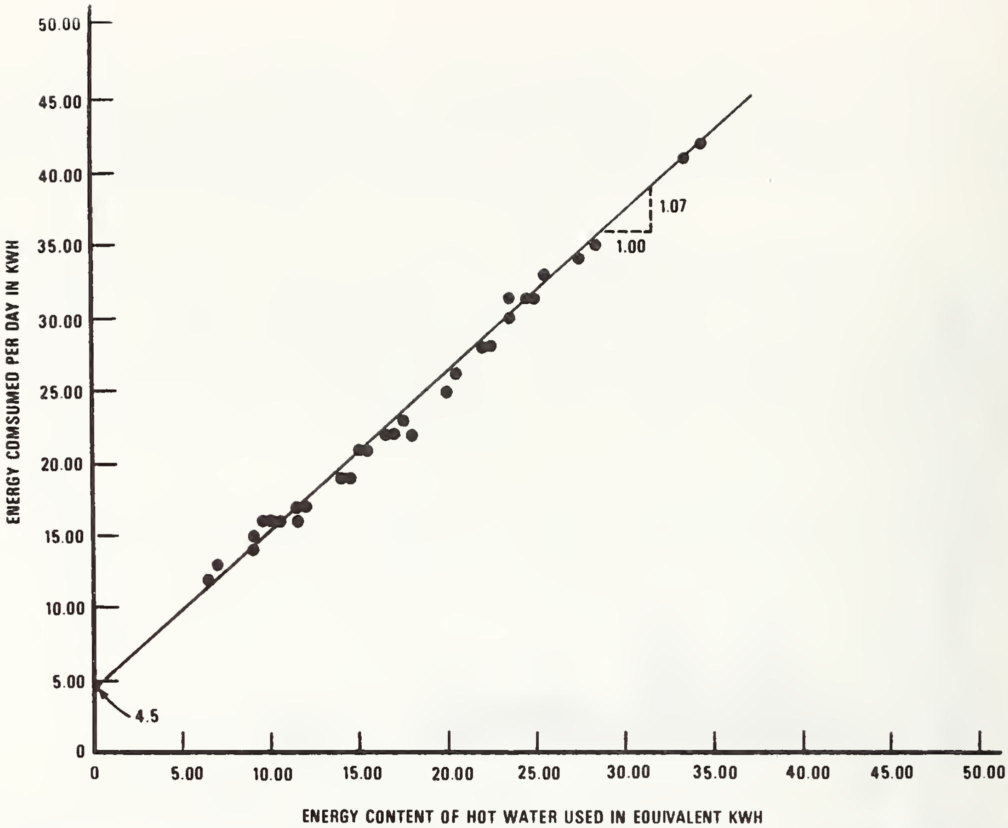

Figure 11. Daily Energy Consumption vs. Daily Drawn Water Energy Content - Townhouse #10

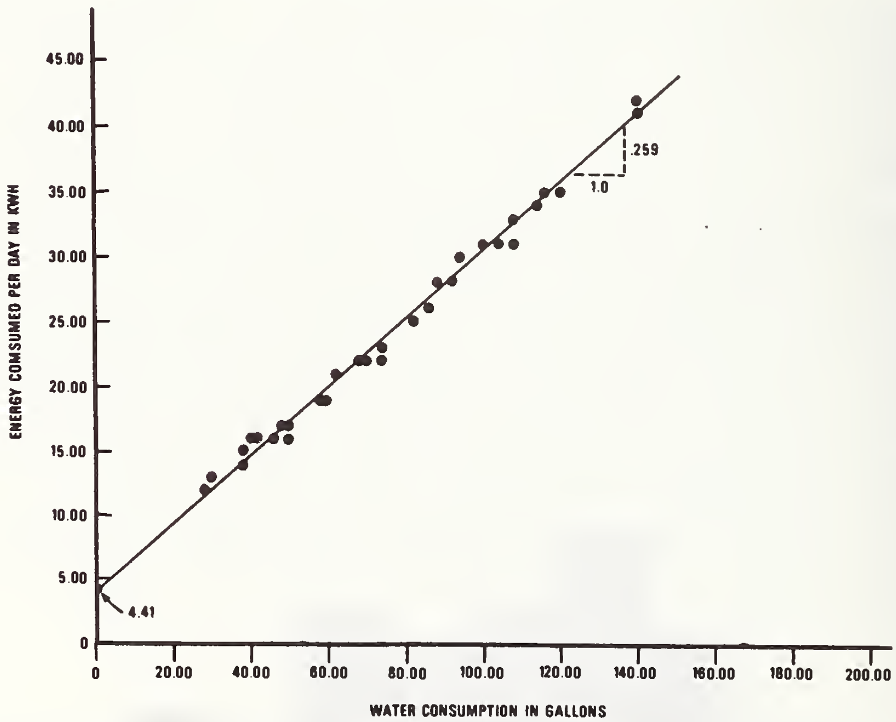

Figure 12. Daily Energy Consumption vs. Daily Hot Water Used - Townhouse #10

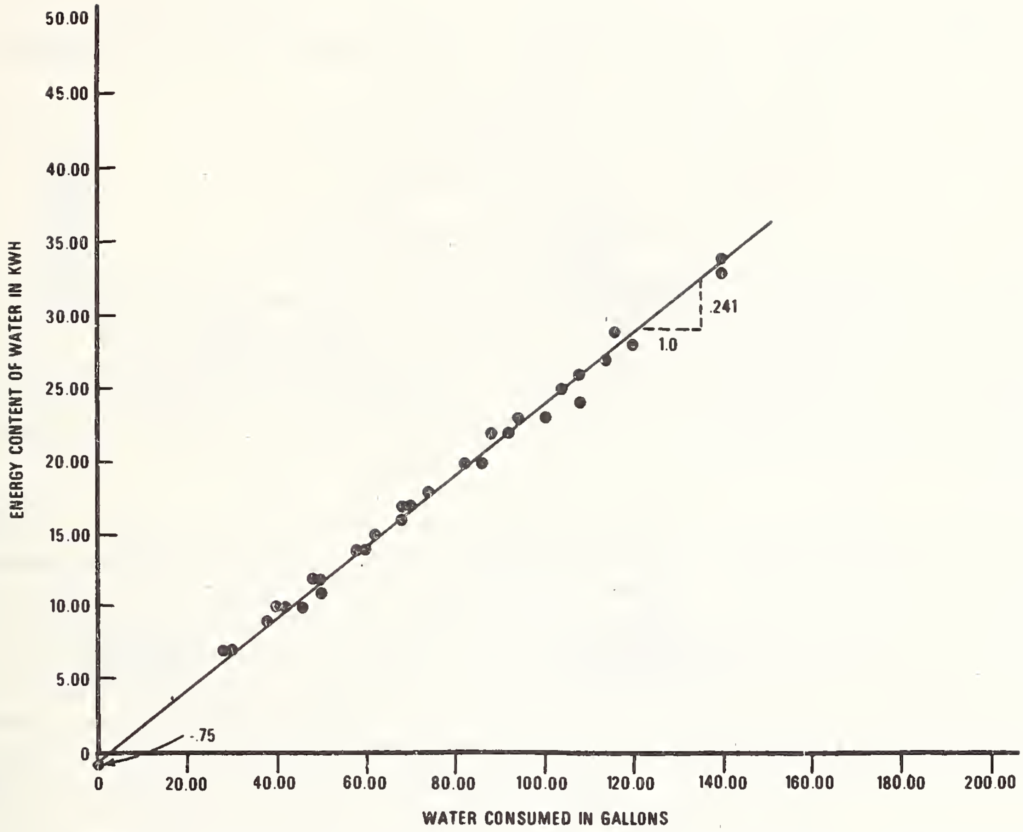

Figure 13. Daily Water Content vs. Daily Hot Water Usage - Townhouse #10

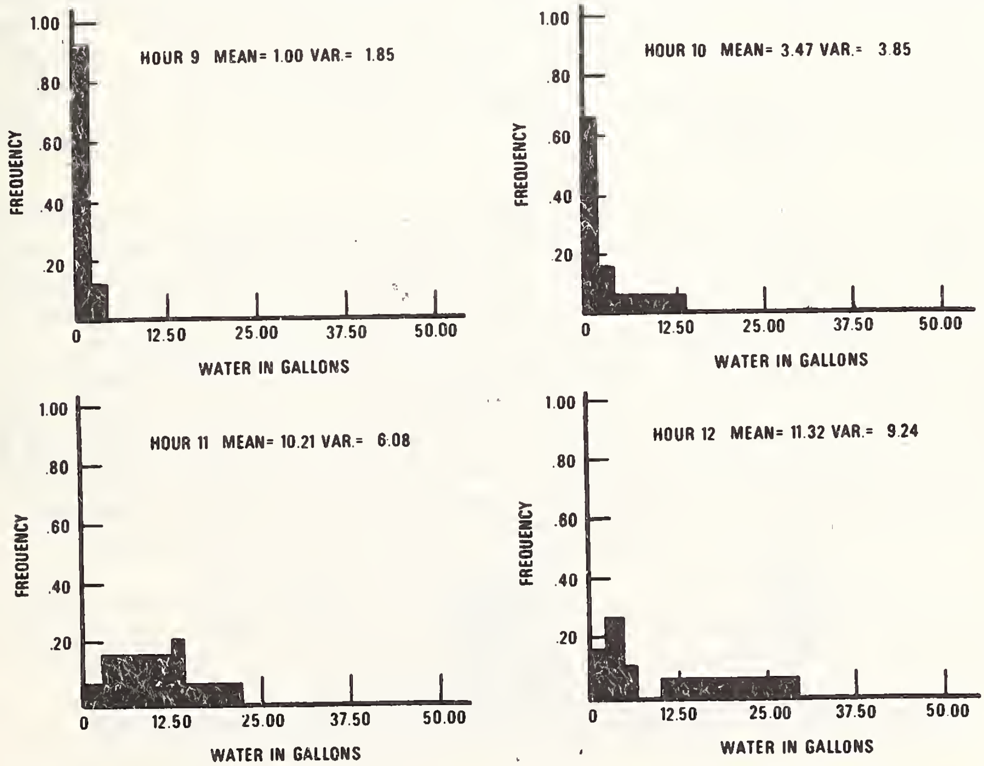

Figure 14. Frequency Plots for Hourly Hot Water Usage - Townhouse #10

The data in Figures 11, 12, and 13 can be approximated by the equations:

$$E = 4.50\ (\pm 0.25) + 0.107\ (\pm 0.013)\ H \qquad (1)$$

$$E - 4.42\ (\pm 0.31) + 0.259\ (\pm 0.004)\ W \qquad (2)$$

$$H = -\ 0.08\ (\pm 0.18) + 0.241\ (\pm 0.002)\ W \qquad (3)$$

where E is the daily energy consumption of the water heater in kWh, H is the heat content of the daily drawn hot water in kWh, and W is the daily water consumption in gallons. The numbers in parentheses in equations (1), (2) and (3) are the standard errors of the estimated coefficients. The average service efficiency of the water heater over this period was 75.0%.

Detailed analysis of the hourly usage is presented in Figures 14 and 15 by the frequency plots. Only a small sample of the available reduced data is presented here. These hourly data plots represent values for all the days of data collected, averaged for each hour of the day. In Figure 14 there is about a 5% frequency of hot water usage above 20 gallons within one hour in the intervals of hours 9, 10, 11, and 12. In other data for this home (not shown on these graphs) it was observed that up to 40 to 50 gallons of hot water usage occurred in the 20th hour with a 5% ocurrence. Figure 15 illustrates for those same hours, 9, 10, 11, 12, the frequency for energy used for water heating. Note that for small water usage in hour 9 there is about 50% operation between zero and 1 kWh. When the water usage is greater (in Figure 14) the range of energy expended is less than 5 kWh with about 20% frequency. The energy content depends on the flow delivered (gallons) and the temperature rise of the water. Since this temperature rise is fairly constant except for periods of excessive usage, there is a close correspondence with Figure 14.

The hourly distribution for a 24-hour period is shown in Figures 16, 17, and 18. These energy and water-usage distributions again represent the average values for each hour of all the days of data collected, i.e., from day 283 to 324, or 41 days. The average hourly usage (i.e., gallons or energy consumed in each hour) is designated by the shaded area. Also shown by the solid line on the graphs 16, 17 and 18 are the plots of 2σ (two standard deviations) about the average. The meaningful utilization of such data will be for design-supply requirements of tanks and pipes. Such new design criteria are required when the energy requirements are no longer economic or are constrained by mandatory or voluntary limiting factors.

Selective samples of data are presented in Figures 19 to 24 from Townhouse 9, to illustrate and compare the effects of different household compositions and different household practices.

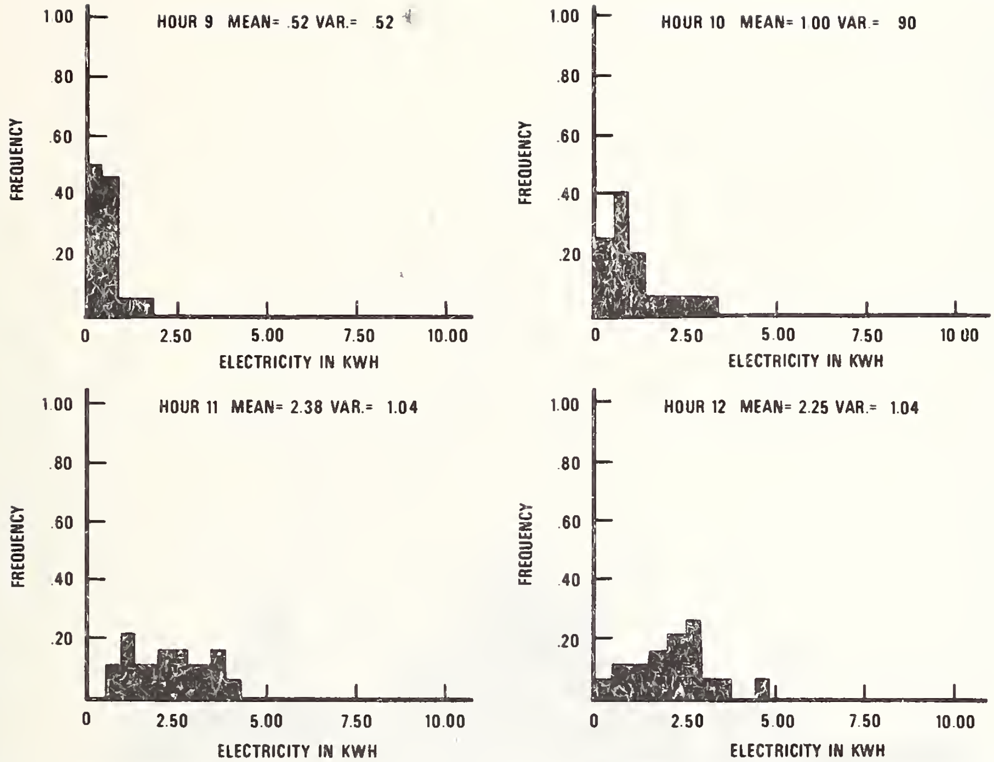

Figure 15. Frequency Plots for Hourly Energy Used for Water Heating - Townhouse #10

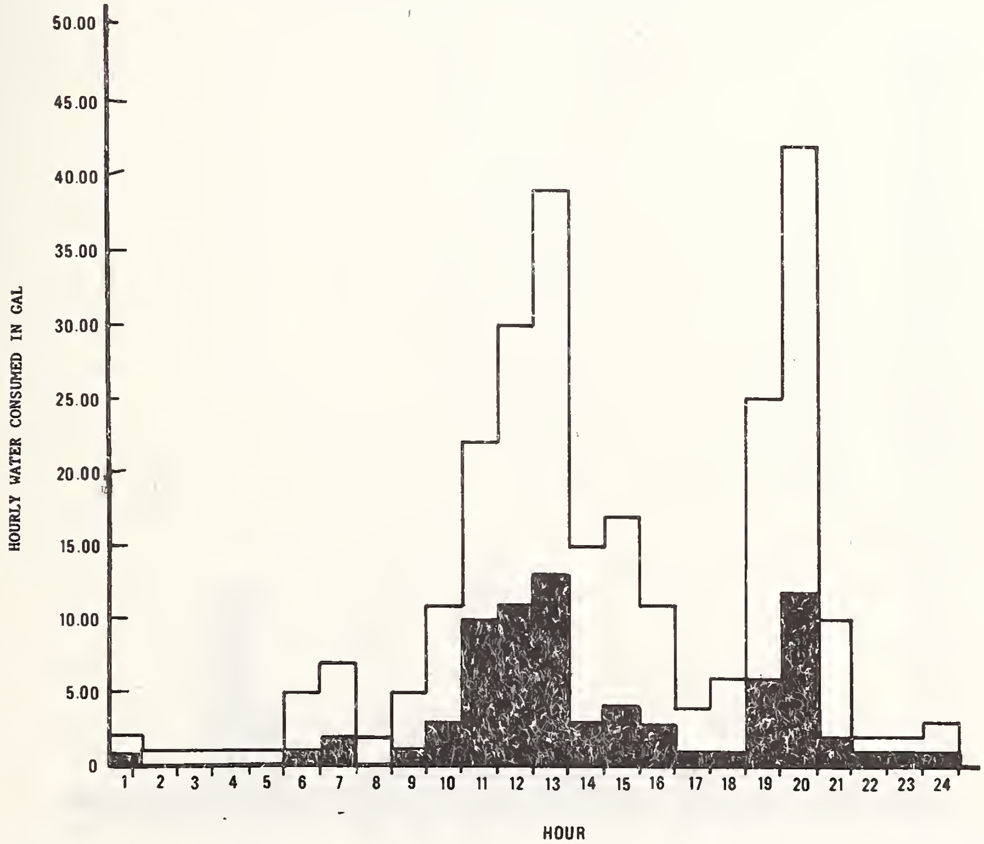

Figure 16. Average Hourly Profile of Hot Water Usage - Townhouse #10

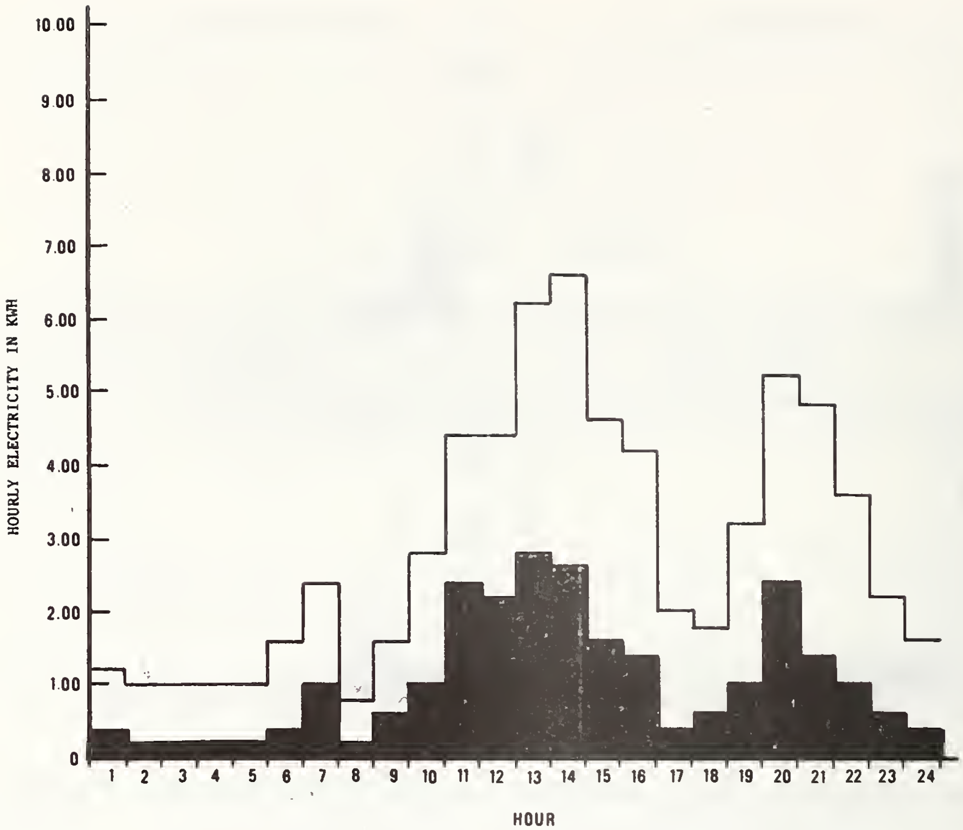

Figure 17. Average Hourly Profile for Water Heating Energy - Townhouse #10

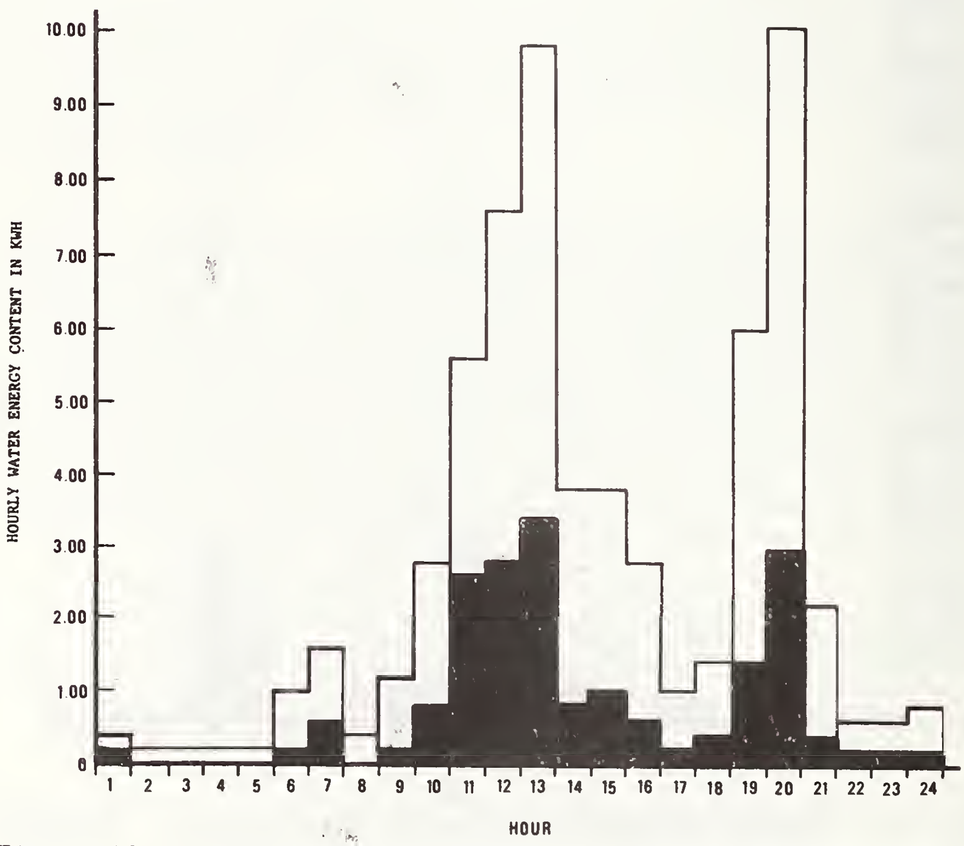

Figure 18. Average Hourly Profile for Energy Contents of Drawn Hot Water - Townhouse #10

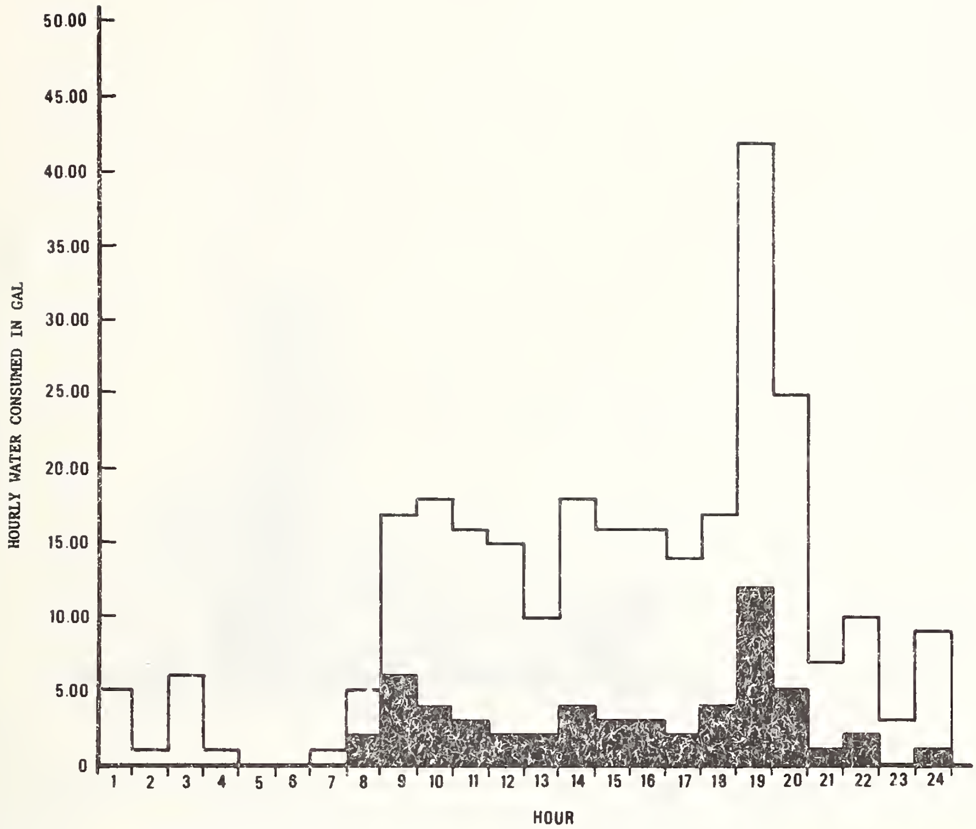

Figure 19. Average Hourly Profile for Hot Water Usage - Townhouse #9

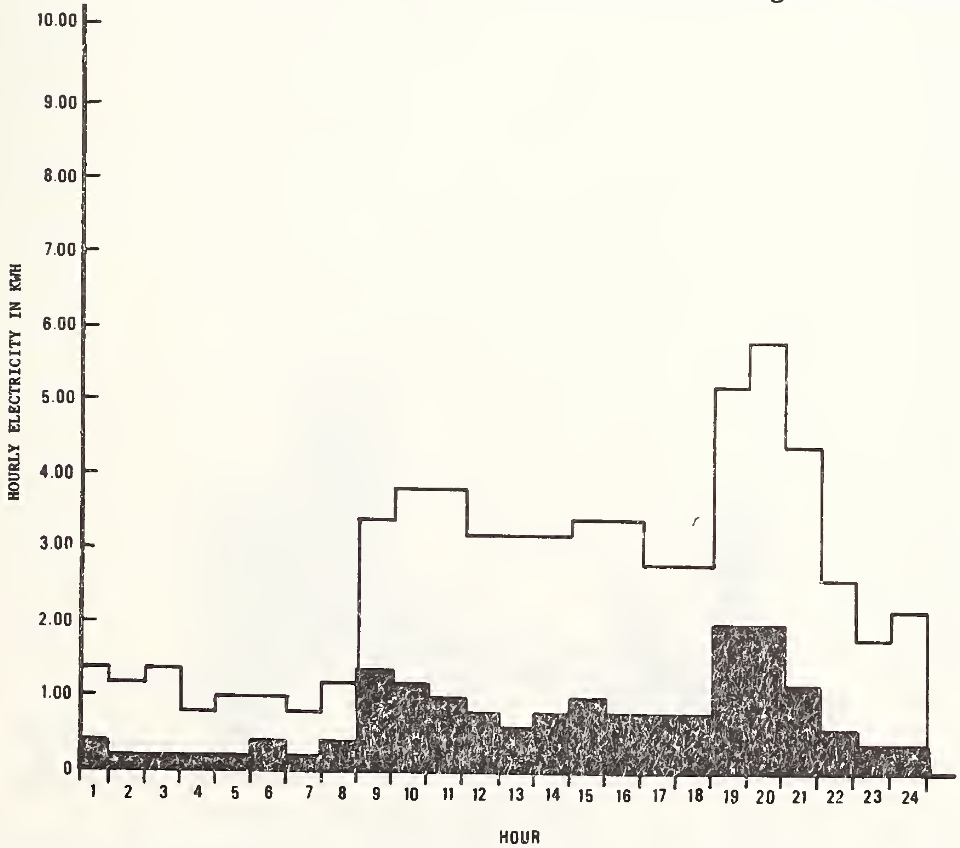

Figure 20. Average Hourly Profile for Water Heating Energy-Townhouse #9

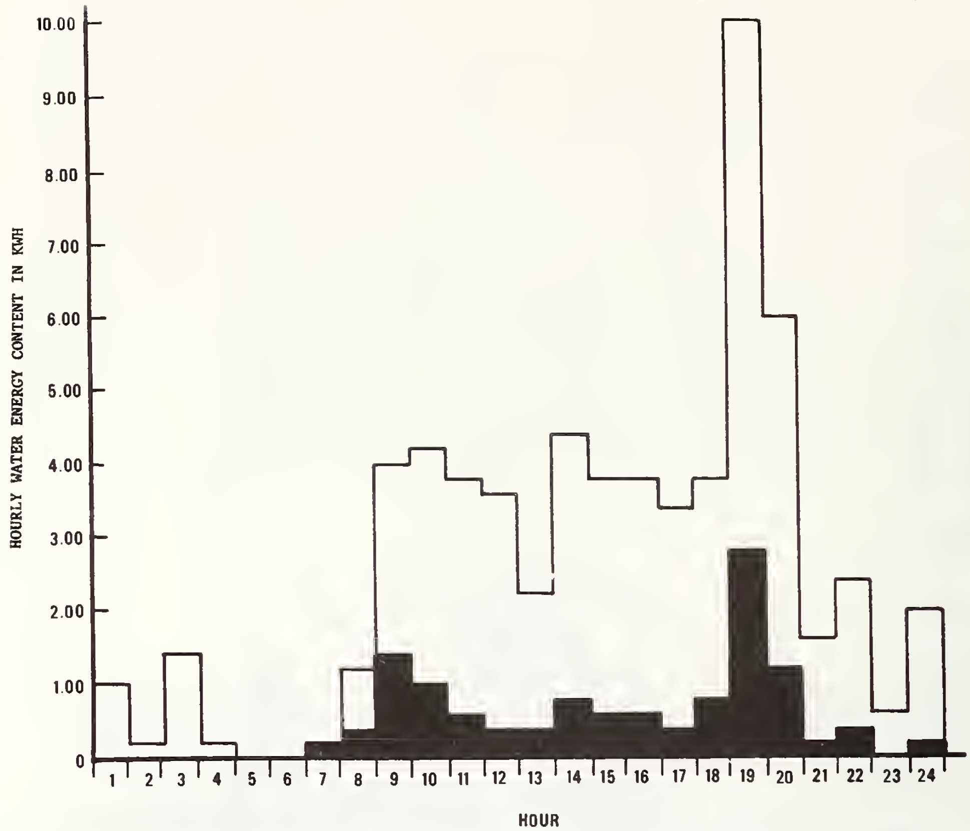

Figure 21. Average Hourly Profile of Energy Content Drawn Hot Water - Townhouse #9

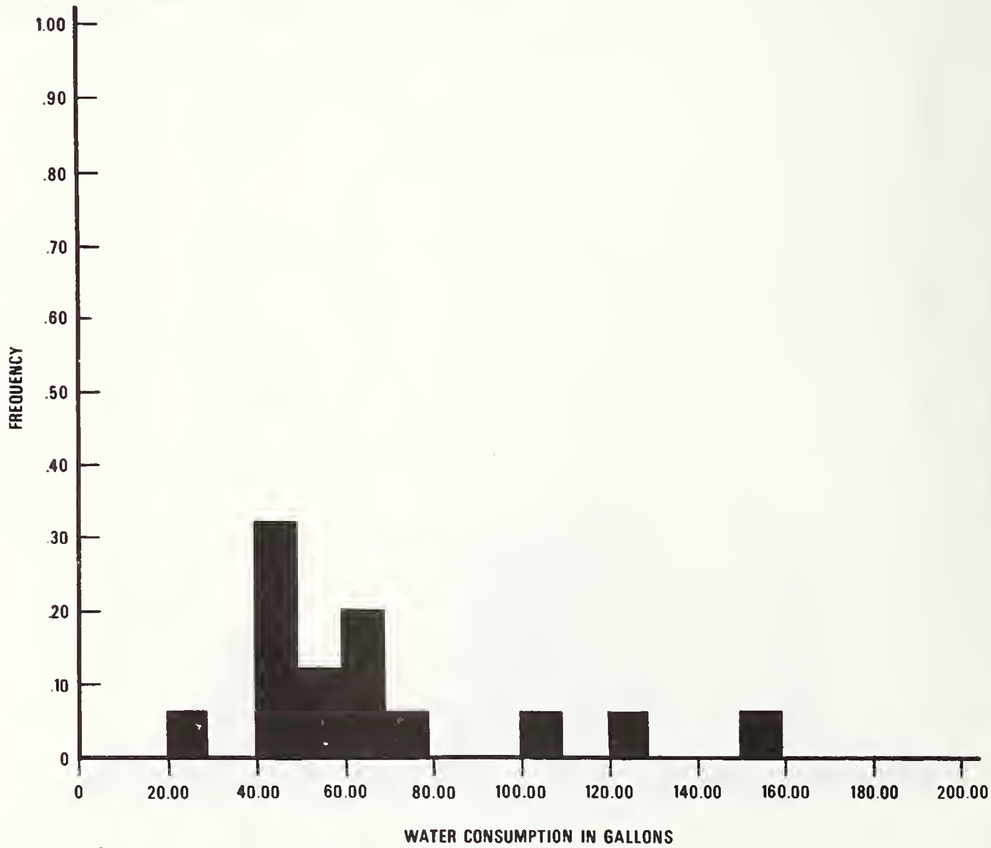

Figure 22. Frequency Plot of Daily Water Consumption - Townhouse #9

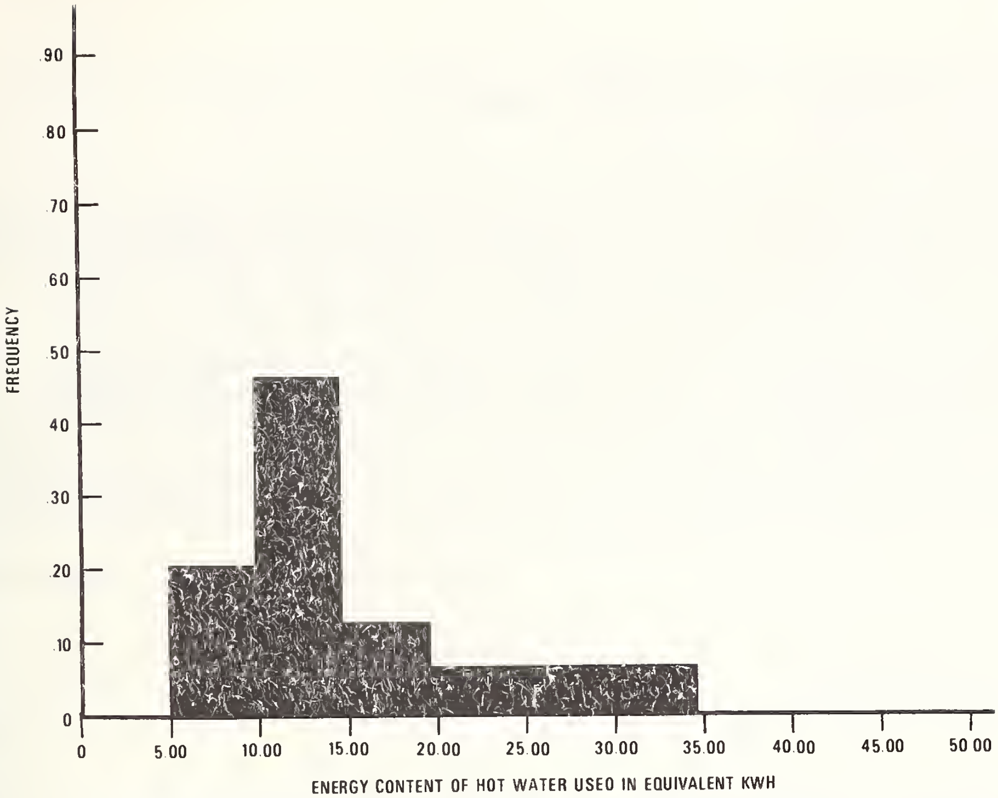

Figure 23. Frequency Plot of Daily Energy for Water Heating - Townhouse #9

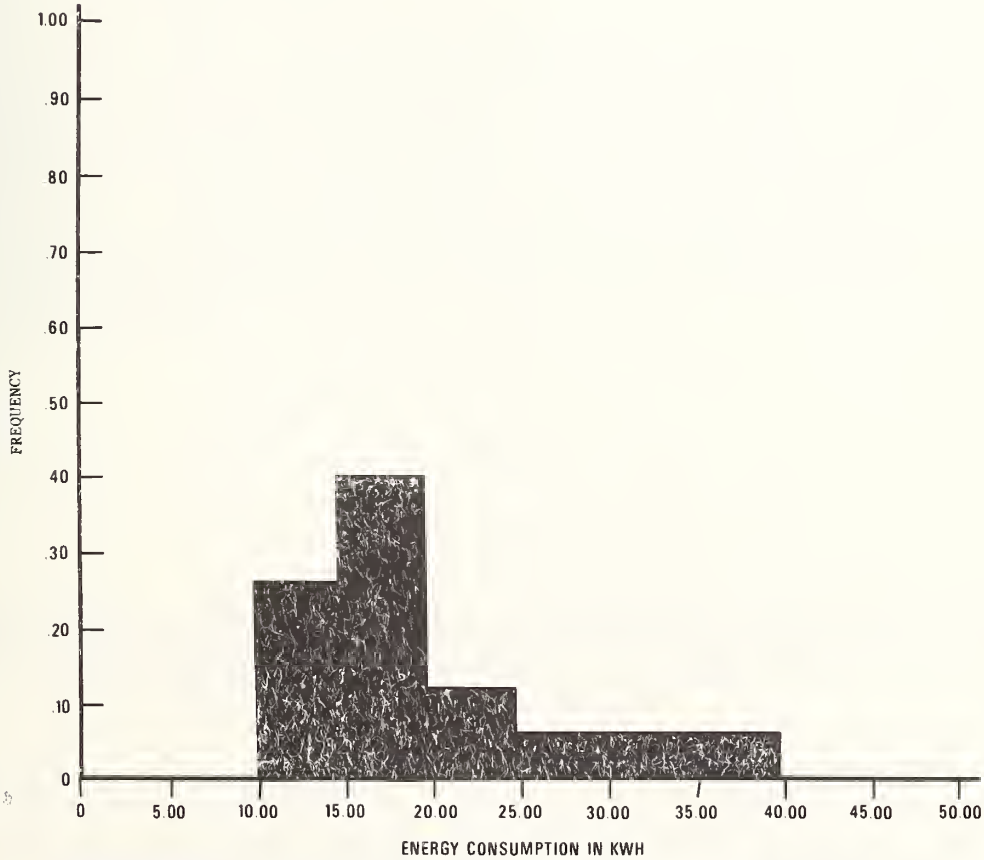

Figure 24. Frequency Plot for Daily Heat Content of Drawn Hot Water - Townhouse #9

5. Summary

The amount of hot water used by a household can vary greatly from day to day and from hour to hour. Though average daily usages and average hourly usage profiles can be derived, experimental data indicate that on the level of an individual dwelling there is a large variation in usage about these averages, both on a daily and hourly basis. A broader range of data is required to establish a generally valid statistical data base. The energy losses from the water heaters measured are nearly constant on a daily basis and though the quantity of daily hot water drawn varies greatly, there exists an essentially linear relationship between the daily amount of energy consumed by the water heater and the daily amount of hot water used.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The early results of a field experiment for determining the performance of gas and electric residential storage water heaters are presented. Energy requirements for hot water supply and hot water consumption and usage pattern data are presented and analyzed using statistical techniques in order to display average load curves and the variation about the average. It is shown that the daily energy usage of these water heaters is approximately a linear function of the energy content of the drawn daily water consumption. This fact allows a simple procedure to be used for evaluating the effects of retrofit actions on the performance of the water heater.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons) Energy usage; load profiles; water heaters.

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